Resonant coherent excitation of 2s electron of Li-like Fe ions to the $n = 3$ states

Yoichi Nakai [a,*], T. Ikeda [a], Y. Kanai [a], T. Kambara [a], N. Fukunishi [b],
K. Komaki [c], C. Kondo [c], T. Azuma [d], Y. Yamazaki [a,c]

[a] *Atomic Physics Laboratory, RIKEN, Wako, Saitama 351-0198, Japan*
[b] *Beam Dynamics Division, Cyclotron Center, RIKEN, Wako, Saitama 351-0198, Japan*
[c] *Institute of Physics, University of Tokyo, Meguro, Tokyo 152-8902, Japan*
[d] *Department of Physics, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan*

Available online 21 January 2005

Abstract

We observed resonant coherent excitation of the 2s electron to the $n = 3$ states of 83.5 MeV/u Li-like Fe^{23+} ions planar-channeling in the $(2\bar{2}0)$ plane of a Si crystal. A survival fraction of the Li-like ions was measured as a function of the angle between the incident beam and the [001] axis. Clear resonance dips corresponding to the transitions of a 2s electron to all the $n = 3$ states were observed. The transition of each resonance dip was identified by comparing with spectroscopic data. The resonance dips at the transition energies corresponding to the optically forbidden $2s_{1/2}$–$3s_{1/2}$, $2s_{1/2}$–$3d_{3/2}$ and $2s_{1/2}$–$3d_{5/2}$ transitions were observed as well as the resonance dips at transition energies corresponding to the optically allowed $2s_{1/2}$–$3p_{1/2}$ and $2s_{1/2}$–$3p_{3/2}$ transitions.
© 2004 Elsevier B.V. All rights reserved.

PACS: 61.85.+p; 34.50.Fa
Keywords: Resonant coherent excitation; Channeling; Electronic excitation and ionization of atoms

1. Introduction

When fast ions are injected into a crystal in parallel to the crystal axis or crystal plane, some of the ions can pass through the crystal without close collisions with atoms of the crystal. Such ion is called a "channeling ion". A channeling ion feels a superposition of oscillating electric fields generated by a periodic lattice structure in the crystal. When the energy difference between two electronic states of the channeling ion matches with one of frequencies of the oscillating fields, the ion is resonant-coherently excited. Such a resonant excitation is referred to as a "resonant

---
* Corresponding author. Fax: +81 48 462 4644.
E-mail address: nakaiy@postman.riken.jp (Y. Nakai).

coherent excitation (RCE)''. The RCE was predicted by Okorokov [1]. After several experimental trials, the first clear observation of RCE was performed by Datz et al. They observed the RCE by the decrease in transmission of fixed-charge-state channeling ions as a function of the ion energy [2]. Since then, the RCE phenomena have been intensively studied experimentally [3–18] and theoretically [19–21]. In particular, recently, Azuma and co-worker have performed a series of RCE experiments using planar-channeling of heavy ions with relativistic velocities. In their experiments, the RCE was observed by rotating the target crystal instead of varying the projectile energy [9–14]. They found sharper structure of the resonance than previous experiments. We reported sharper resonance structure for the RCE of a 1s electron bound in a 94 MeV/u hydrogen-like Ar ion to $n = 2$ states under the planar-channeling condition in the $(2\bar{2}0)$ plane of a Si crystal [15].

Most of the experimental studies of RCE have been done using hydrogen atoms and hydrogen-like ions. The hydrogen-like ions are thought to be good as test ions for investigation of the RCE dynamics because of their simple atomic structure. However, since the excited states with the same principal quantum number almost degenerate, these states can be easily mixed due to strong Stark effect by the position-dependent static crystal field. The resonance structure is considerably different from that of the states in a vacuum. On the other hand, in the case of the ions with two or more electrons, the Stark effect should be weaker than the hydrogen-like ions. The channeling ions should hold electronic structures in a vacuum, compared with the hydrogen-like ions. Nevertheless, the experiments using the ions with two or more electrons have been little performed [3,4]. In particular, no RCE experiments for the ions with three or more electrons have been reported to the best of our knowledge. We performed the experiment for the RCE of a 2s electron of Li-like heavy ions. In this paper, we will report the experiment for the RCE of a 2s electron of 83.5 MeV/u Li-like Fe^{23+} ion to $n = 3$ states under the condition of planar-channeling in the $(2\bar{2}0)$ plane of the Si crystal.

2. Experiment

Since our experimental setup has been already reported elsewhere [15], it is described briefly here. A beam of 83.5 MeV/u Fe^{23+} ions was provided at RIKEN Ring Cyclotron (RRC). The transport elements of the beamline from the RRC to the target chamber were carefully tuned so that the angular divergences of the Fe beam became as small as possible. The angular divergence is experimentally estimated to be several tens μrad. The beam was collimated with a 3 mm thick tungsten plate with a 0.5 mm⌀ hole about 45 cm upstream of the Si target. The beam optics calculation also shows that the longitudinal momentum spread of the incident beam should be ≈100 ppm in full width. The beam intensity was about 10^3 particles/s.

A Si (0 0 1) crystal of 7 μm in thickness was used as a target and mounted on the high-precision goniometer [22]. The ions emerging from the crystal were deflected by a small dipole magnet placed at the downstream of the Si target in order to analyze the final charge states. A two-dimensional position sensitive detector (2D-PSD) was located at about 8 m downstream of the dipole magnet. Survived Fe^{23+} ions and charge-changed Fe^{24+}, Fe^{25+} and Fe^{26+} ions were detected there. The position information from the 2D-PSD was collected as a function of the orientation of the Si crystal.

An electron in the $n = 3$ or higher states is much more easily ionized in the crystal than that in the 2s state. Therefore, the survival fraction of Li-like ions, which is given by

$$f(\text{Li-like}) = N(\text{Li-like})/[N(\text{Li-like}) + N(\text{He-like}) + N(\text{H-like}) + N(\text{bare})],$$

decreases when the 2s electron of Li-like ion is resonantly excited, where N is the number of Li-like, He-like, H-like and bare ions emerging from the crystal. Rotating the Si crystal in the (2 2 0) plane, the RCE is observed as a decrease in the survival fraction f(Li-like).

The excitation energy E_{trans} due to the oscillating crystal field is obtained by multiplying the Planck constant and the frequency of the oscillating field in the projectile frame as

$$E_{\text{trans}} = hc\gamma\beta\left(\frac{k\cos\theta}{A} + \frac{l\sin\theta}{B}\right), \qquad (1)$$

where θ is an angle between the beam direction and the [0 0 1] axis of the Si crystal in the plane, v is the ion velocity, c is the light velocity, $\beta = v/c$, $\gamma = 1/\sqrt{1 - \beta^2}$, and h is the Planck constant. (A, B) is $(a, a/\sqrt{2})$ with the lattice constant a. k and l are integers which show resonance indices.

3. Result and discussion

In Figs. 1(a) and (b), the survival fractions of Li-like ions are shown from $\theta = 6.7°$ to $\theta = 8.3°$ and from $\theta = 3.1°$ to $\theta = 4.0°$, respectively. Different symbols correspond to different runs of the experiment. We suppose that a small step structure between open circle and solid circle near 7.0° does not come from a physical reason but that it is caused by a slight change of the beam condition. In Fig. 1, we can see ten clear resonance dips. These dips are labeled from "A" to "J". The structure of dips from A to E in Fig. 1(a) and that of dips from F to J in Fig. 1(b) seem to be quite similar to each other. It indicates that the dips from A to E and the dips from F to J correspond to the same transition series with different indices (k, l) as mentioned below.

In this experiment, it is necessary to determine the beam energy precisely. Since there is no

means of direct measurement of the beam energy with required precision, we used Eq. (1) to determine the beam energy by assuming that the energy of one of the observed resonance dips matches with the transition energy in optical transition data. We used $2s_{1/2}$–$3p_{1/2}$ transition in order to determine the beam energy. We assumed that dips B and G correspond to $2s_{1/2}$–$3p_{1/2}$ transitions with $(k, l) = (1, 1)$ and $(1, 2)$, respectively. The beam energy was determined so that the E_{trans}'s at the bottoms of both dips B and G were fitted to the spectroscopic datum of the $2s_{1/2}$–$3p_{1/2}$ transition energy, which is 1162.75 eV calculated from the wavelength data by Boiko et al. [23], using a least-square fitting procedure. Our estimated beam energy is 83.5 MeV/u as described in Section 2. The uncertainty of our estimated beam energy is $\approx\pm0.04\%$. This uncertainty is much smaller than that in the beam-energy estimation with the accelerator parameters. In this experiment, the difference between our estimated value of the beam energy and the value calculated from the accelerator parameters is $\approx0.6\%$. Indeed, this difference is the same order of the ambiguity of beam energy calculated from the accelerator parameters, which is typically $\approx\pm0.5\%$.

In Figs. 2(a) and (b), the survival fractions of Li-like ions are shown as functions of E_{trans} in Eq. (1) for $(k, l) = (1, 1)$ and $(1, 2)$, respectively, in
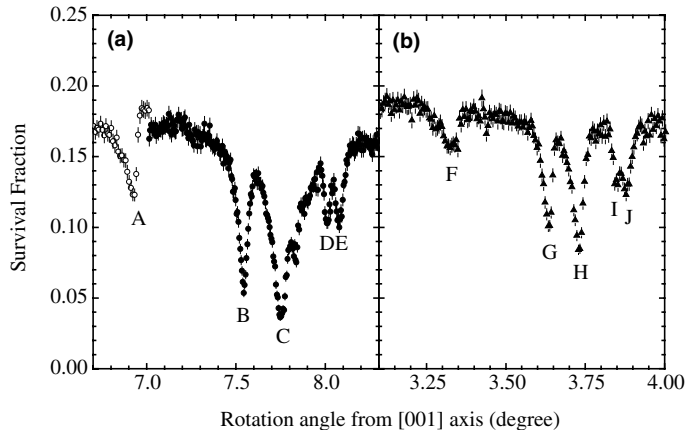

Fig. 1. (a) The survival fraction of Li-like ions is shown from $\theta = 6.7°$ to $\theta = 8.3°$. Open circle and solid circle correspond to the results for different runs of the experiment, respectively. (b) The survival fraction of Li-like ions is shown from $\theta = 3.1°$ to $\theta = 4.0°$.
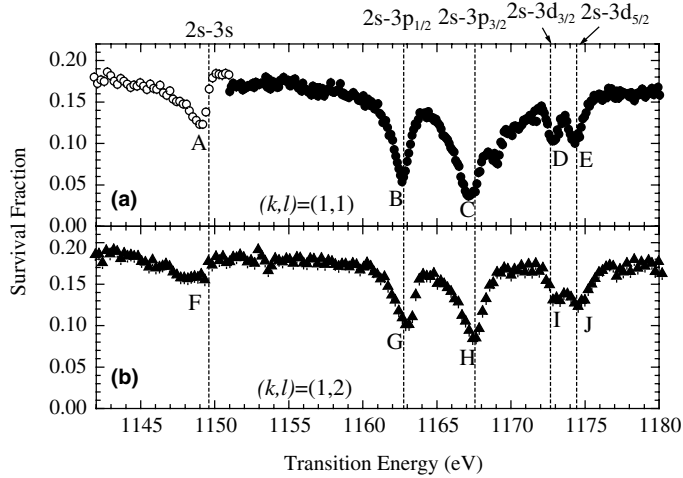
Fig. 2. (a) The survival fractions of Li-like ions are shown as a function of excitation energy E_{trans} estimated using Eq. (1) for $(k,l) = (1,1)$ in the energy region from 1142 eV to 1180 eV. Vertical dashed straight lines show the transition energies from $2s_{1/2}$ state to $n = 3$ states calculated from spectroscopic data. (b) The survival fractions of Li-like ions are shown as a function of excitation energy E_{trans} estimated using Eq. (1) for $(k,l) = (1,2)$ in the energy region from 1142 eV to 1180 eV. Vertical dashed straight lines show the same energies as (a).

the energy region from 1142 eV to 1180 eV. Vertical dashed straight lines show the transition energies from $2s_{1/2}$ state to $n = 3$ states. The transition energies between the $2s_{1/2}$ state and $n = 3$ states are derived from wavelength data of optically allowed transition from $n = 2$ states to $n = 3$ states by Boiko et al. [23] and wavelength data of the 2s–2p transitions by Sandlin et al. [24]. As shown in Fig. 2, there is a resonance dip for $(k,l) = (1,2)$ corresponding to each resonance dip for $(k,l) = (1,1)$. It clearly shows that the dips from A to E and the dips from F to J correspond to the same transition series with different indices (k,l). Moreover, it is found that RCE energy of each resonance dip corresponds to the transition energy from the $2s_{1/2}$ state to each $n = 3$ state as shown in Fig. 2. It confirms that the resonance dips from A to J correspond to the transition from the $2s_{1/2}$ state to $n = 3$ states.

We also observed shallow resonance dips that seem to correspond to the transitions with $(k,l) = (1,1)$ from the $2p_{1/2}$ and $2p_{3/2}$ states to $n = 3$ states in the region from $\theta = 4.0°$ to $\theta = 6.2°$ although we do not show these shallow dips in the figures. In particular, a clear resonance dip can be seen at the $2p_{3/2}$–$3d_{5/2}$ transition energy.

It implies that a small part of Fe^{23+} ions are excited to the $2p_{1/2}$ and $2p_{3/2}$ states by the collisions in the crystal.

The assignment of each resonance dip from dip-A to dip-J to a transition and a resonance index (k,l) is shown in Table 1. We note the followings about the assignment and the observed resonance structures:

(1) Considering possible RCEs that occur at dip-A, not only the $2s_{1/2}$–$3s_{1/2}$ transition with $(k,l) = (1,1)$ but also the transition from the $2p_{3/2}$ state to the $n = 4$ states with $(k,l) = (1,3)$ may be included because 2s electrons of a small part of Fe^{23+} ions are excited to the $2p_{1/2}$ and $2p_{3/2}$ states by the collisions in the crystal. However, we think that the contribution of the transition from $2p_{3/2}$ state to $n = 4$ states with $(k,l) = (1,3)$ is negligibly small because we cannot clearly see the resonance dips corresponding to the transitions from the $2p_{1/2}$ state to the $n = 4$ states with $(k,l) = (1,3)$ between dips A and B.

(2) Dips A and F ($2s_{1/2}$–$3s_{1/2}$ transition) are skew and have long tails towards low-energy side, which is different feature from other

Table 1
The transition energy at the bottom of each RCE dip calculated by Eq. (1) for the RCE with $(k,l) = (1,1)$ and $(1,2)$ and the corresponding transition energy derived from the wavelength data of optical transition in [23,24]

Transition	Transition energy at RCE dip (eV)				Transition energy from spectroscopic data (eV)
	$(k,l) = (1,1)$		$(k,l) = (1,2)$		
$2s_{1/2}$–$3s_{1/2}$	Dip-A	1149.20 ± 0.3	Dip-F	1148.42 ± 0.4[a]	1149.61 ± 0.3[b]
$2s_{1/2}$–$3p_{1/2}$	Dip-B	1162.65 ± 0.3[c]	Dip-G	1162.89 ± 0.4[c]	1162.75 ± 0.3
$2s_{1/2}$–$3p_{3/2}$	Dip-C	1167.14 ± 0.3	Dip-H	1167.41 ± 0.4	1167.57 ± 0.3
$2s_{1/2}$–$3d_{3/2}$	Dip-D	1172.81 ± 0.3	Dip-I	1173.08 ± 0.4	1172.67 ± 0.3[d]
$2s_{1/2}$–$3d_{5/2}$	Dip-E	1174.33 ± 0.3	Dip-J	1174.53 ± 0.4	1174.44 ± 0.3[e]

  [a] The bottom of dip-F is flat. This transition energy was determined at the center of the flat dip bottom.

  [b] This value was calculated by the sum between the energy of the $2s_{1/2}$–$2p_{1/2}$ transition ($\delta E \approx 0.006$ eV) and the energy of the $2p_{1/2}$–$3s_{1/2}$ transition ($\delta E \approx 0.3$ eV), where δE shows an uncertainty of transition energy.

  [c] The beam energy was determined so that the RCE energies at the bottoms of both dips B and G were fitted to 1162.75 eV. See text for the detail.

  [d] This value was calculated by the sum between the energy of the $2s_{1/2}$–$2p_{1/2}$ transition and the energy of the $2p_{1/2}$–$3d_{3/2}$ transition ($\delta E \approx 0.3$ eV).

  [e] This value was calculated by the sum between the energy of the $2s_{1/2}$–$2p_{3/2}$ transition ($\delta E \approx 0.01$ eV) and the energy of the $2p_{3/2}$–$3d_{5/2}$ transition ($\delta E \approx 0.3$ eV).

resonance dips. Considering that this skew structure is common feature in this transition, the long tail towards low-energy side is not thought to result from an accidental mixture of other transition with other index (k,l).

(3) On the high-energy side of dip-C, there is a small structure. This seems to be the transition with $(k,l) = (1,3)$ from the $2s_{1/2}$ state to $n = 4$ states.

(4) The dips I and J correspond to the same transitions as the dips D and E, but the dip profile is a little different: The separation between I and J is not clear as that between D and E. We suppose that its reason is that the widths of dips I and J are slightly wider than dips D and E because the tails of dips I and J are more gentle than those of dips D and E as shown in Fig. 2.

Table 1 also shows the transition energy at the bottom of each RCE dip calculated by Eq. (1) for the RCE with $(k,l) = (1,1)$ and $(1,2)$ and the corresponding transition energy derived from the wavelength data of optical transitions in [23,24]. The uncertainties of the RCE transition energies mainly result from the uncertainty of the spectroscopic datum for $2s_{1/2}$–$3p_{1/2}$ transition. The uncertainties of the transition energies derived from wavelength data of optical transitions [23,24] mainly come from the uncertainties of the wavelength measurement for transitions between the $n = 2$ states and the $n = 3$ states [23]. The RCE transition energy at the bottom of each RCE dip agrees with the corresponding transition energy from spectroscopic data within the uncertainty except dip-F. The difference between the RCE transition energy of dip-F and spectroscopic data slightly exceeds the uncertainty. However, the bottom of dip-F is flat and unclear.

As shown in Fig. 2, the resonance dips at the transition energies corresponding to optically forbidden $2s_{1/2}$–$3s_{1/2}$ transition (dip-A and dip-F) and $2s_{1/2}$–$3d_{3/2}$ and $2s_{1/2}$–$3d_{5/2}$ transitions (dip-D, dip-E, dip-I and dip-J) can be detected as well as those at the transition energies corresponding to the optically allowed $2s_{1/2}$–$2p_{1/2}$ and $2s_{1/2}$–$2p_{3/2}$ transitions (dip-B, dip-C, dip-G and dip-H). The RCE of the 2s electron to all the $n = 3$ states can be clearly observed at almost same transition energy as the spectroscopic data although there may be complexity due to processes in a solid. This fact indicates the possibility that the RCE process is used as a new method of direct spectroscopy of the optically forbidden transition.

Acknowledgements

References

[1] V.V. Okorokov, Yad. Fiz. 2 (1965) 1009 [Sov. J. Nucl. Phys. 2 (1966) 719].

[2] S. Datz, C.D. Moak, O.H. Crawford, H.F. Krause, P.F. Dittner, J. Gomez del Campo, J.A. Biggerstaff, P.D. Miller, P. Hvelplund, H. Knudsen, Phys. Rev. Lett. 40 (1978) 843.

[3] C.D. Moak, S. Datz, O.H. Crawford, H.F. Krause, P.F. Dittner, J. Gomez del Campo, J.A. Biggerstaff, P.D. Miller, P. Hvelplund, H. Knudsen, Phys. Rev. A 19 (1979) 977.

[4] C.D. Moak, J.A. Biggerstaff, O.H. Crawford, P.F. Dittner, S. Datz, J. Gomez del Campo, P. Hvelplund, H. Knudsen, H.F. Krause, P.D. Miller, S.H. Overbury, Nucl. Instr. and Meth. 194 (1982) 327.

[5] F. Fujimoto, K. Komaki, A. Ootuka, E. Vilalta, Y. Iwata, Y. Hirao, T. Hasegawa, M. Sekiguchi, A. Mizobuchi, T. Hattori, K. Kimura, Nucl. Instr. and Meth. B 33 (1988) 354.

[6] K. Kimura, J.P. Gibbons, S.B. Elston, C. Bierdermann, R. DeSerio, N. Keller, J.C. Levin, M. Breinig, J. Burgdorfer, I.A. Sellin, Phys. Rev. Lett. 66 (1991) 25.

[7] S. Datz, P.F. Dittner, H.F. Krause, C.R. Vane, O.H. Crawford, J.S. Forster, G.S. Ball, W.G. Davies, J.S. Geiger, Nucl. Instr. and Meth. B 100 (1995) 272.

[8] J.U. Andersen, G.C. Ball, J. Chevallier, J.A. Davies, W.G. Davies, J.S. Forster, J.S. Geiger, H. Geissel, Nucl. Instr. and Meth. B 119 (1996) 292.

[9] K. Komaki, T. Azuma, T. Ito, Y. Takabayashi, Y. Yamazaki, M. Sano, M. Torikoshi, A. Kitagawa, E. Takada, T. Murakami, Nucl. Instr. and Meth. B 146 (1998) 19.

[10] T. Azuma, T. Ito, K. Komaki, Y. Yamazaki, M. Sano, M. Torikoshi, A. Kitagawa, E. Takada, T. Murakami, Phys. Rev. Lett. 83 (1999) 528.

[11] T. Ito, Y. Takabayashi, K. Komaki, T. Azuma, Y. Yamazaki, S. Datz, E. Takada, T. Murakami, Nucl. Instr. and Meth. B 164–165 (2000) 68.

[12] T. Azuma, T. Ito, Y. Takabayashi, K. Komaki, Y. Yamazaki, E. Takada, T. Murakami, Phys. Scr. T 92 (2001) 61.

[13] T. Azuma, Y. Takabayashi, T. Ito, K. Komaki, Y. Yamazaki, E. Takada, T. Murakami, Nucl. Instr. and Meth. B 212 (2003) 397.

[14] T. Azuma, T. Muranaka, Y. Takabayashi, T. Ito, C. Kondo, K. Komaki, Y. Yamazaki, S. Datz, E. Takada, T. Murakami, Nucl. Instr. and Meth. B 205 (2003) 779.

[15] Y. Nakai, T. Ikeda, Y. Kanai, T. Kambara, N. Fukunishi, T. Azuma, K. Komaki, Y. Takabayashi, Y. Yamazaki, Nucl. Instr. and Meth. B 205 (2003) 784.

[16] K. Kimura, H. Ida, N. Fritz, M. Mannami, Phys. Rev. Lett. 76 (1996) 3850.

[17] C. Auth, H. Winter, Phys. Rev. Lett. 79 (1997) 4477.

[18] N. Hatke, M. Dirska, M. Grether, E. Luderer, A. Robin, A. Narmann, W. Heiland, Phys. Rev. Lett. 79 (1997) 3395.

[19] O.H. Crawford, R.H. Ritchie, Phys. Rev. A 20 (1979) 1848.

[20] F.J. García de Abajo, P.M. Echenique, Phys. Rev. Lett. 76 (1996) 1856.

[21] A. Salin, A. Arnau, P.M. Echenique, Phys. Rev. A 57 (1998) 2772.

[22] T. Ikeda, Y. Nakai, Y. Kanai, T. Kambara, N. Fukunishi, T. Azuma, K. Komaki, Y. Takabayashi, Y. Yamazaki, in preparation.

[23] V.A. Boiko, A.Ya. Faenov, S.A. Pikuz, J. Quant. Spectrosc. Radiat. Transfer 19 (1978) 11.

[24] G.D. Sandlin, G.E. Brueckner, V.E. Scherrer, R. Tousey, Astrophys. J. 205 (1976) L47.